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CONTROLLING THERMAL POLLUTION IN SMALL STREAMS

George W. Brown, et al

National Environmental Research Center
Corvallis, Oregon

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Controlling Thermal Pollution in Small Streams

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A method for measuring the density of the canopy in the path of the sun is described. The use of this method in the design of buffer strips will provide protection for the stream and maximum harvesting of the timber resource.

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Buffer strips have been proposed as a method for controlling temperature changes in streams adjacent to clear-cuttings. Nine small mountain streams in Oregon's Coast Range and Cascade Mountains were studied to determine the influence of buffer strips on water temperature. Timber volume in the strip, strip width, and canopy density perpendicular to the sun's rays were compared to the effectiveness of the strip in controlling temperature change. This effectiveness was not well correlated with timber volume or strip width. The density of the canopy in the path of the sun is the most important buffer strip characteristic for water temperature control.

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SECTION I
CONCLUSIONS

1. Large temperature changes often observed after clear-cut logging alongside small streams in the Pacific Northwest can be controlled using buffer strips of vegetation between the clear-cut boundary and the stream.
2. The density of the forest canopy in the path of the sun is the most important characteristic for water temperature control.
3. The effectiveness of buffer strips for temperature control is not well correlated with the volume of commercial timber remaining in the strip or the width of the strip.
4. The canopy density of the strip can be planned prior to logging so that it minimizes the temperature change resulting from logging and also minimizes the volume of commercial timber required for this protection. This minimum timber volume can be determined with a tilting mirror that can be used in the stream channel.

SECTION II
RECOMMENDATIONS

The results of this study indicate that the efficiency of a buffer strip for controlling stream temperature is most closely related to the density of the canopy shading the stream and not the volume of commercial timber in the strip nor strip width. Maintaining natural stream temperatures during logging requires only that vegetation actually providing shade for the stream during the critical mid-day hours be left alongside the stream. This vegetation can be readily identified using the canopy densiometer and streamside vegetation survey technique described in this report. It is recommended that such surveys be made as part of the normal pre-logging planning procedure where timber harvesting will be conducted adjacent to valuable streams. It is also recommended that the angular canopy density be maintained at 80% coverage or at the pre-logging level where the canopy density is less than 80% before logging.

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SECTION III

INTRODUCTION

Purpose

Stream temperature is an important criterion for water quality. The temperature of the stream affects its use for municipal consumption as well as for a desirable fish habitat. High water temperatures, which often are a result of land use activities, adversely affect the quality of the water for both of these uses.

In recent years, there has been an increased interest in water quality by the public. Certain segments of the public have demanded that land use activities be conducted in such a manner as to have no effect on the quality of the water in streams. Public pressure has been especially intense in the Pacific Northwest where both commercial forests, the principal land use, and high quality water are important resources.

The adverse effects of logging on stream temperature have been known for many years. Ways of preventing these effects have also been known. Several researchers in the early part of this century reported on the value of strips of vegetation along streams to provide shade and to control the water temperature (1, 27, 30, 31, 34). In recent years, guidelines for the protection of watersheds during logging have recommended similar strips (15, 20, 29). The problem with these guidelines is that they tend to be too general concerning desired properties of these buffer strips. The closest they come to listing desirable characteristics of buffer strips is to specify a minimum width for the strip. This type of specification usually results in a less than optimum utilization of the timber resources by creating larger buffer strips than are necessary for protection of the stream.

The purposes of this study are to determine which buffer strip characteristics are important in regulating the temperature of small streams and to develop a method for designing the minimum buffer strip that will

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provide adequate temperature control.

Scope

Buffer strips have been proposed as a solution to many water quality problems. It has been suggested that accumulation of slash in stream channels and destruction of channel banks can be prevented if buffer strips are left between the logging unit and the stream. Buffer zones are usually required along streams during the application of chemicals to forest lands. All of these benefits are important. However, this study is limited to determining the relationships between buffer strips and temperature control on small forest streams.

The study did not consider the silvical aspects of managing buffer strips. These include such considerations as individual tree removal within the strip, complete harvesting, or regeneration of the strip. These problems must be considered on a site by site basis according to existing environmental and operational conditions. Problems attendant with sudden exposure to full sunlight, insect infestations, or blowdown are also not considered. However, these problems do not appear to be of much concern in the Pacific Northwest (13, 24).

SECTION IV
REVIEW OF LITERATURE

Undesirable Effects of High Water Temperatures

High water temperatures can have undesirable effects on the quality of water for fish production and for human consumption. Excessively high water temperatures can be lethal to fish. The lethal temperature varies among species and with the acclimation temperature of the individual fish. Brett (4) reported on the tolerance of various species of fish to warm water temperatures. He found the lethal limit for several species of salmon to be in the range of 75° to 77°F. Research in the Alsea Logging-Aquatic Resources Study revealed no significant mortality to coho salmon (Oncorhynchus kisutch) fingerlings when the water temperature exceeded 80°F (19). This indicates that the fish are more tolerant of high temperatures than was previously thought. However, little is known about the effect of the temperature on the vitality of the fish or of their ability to survive at sea and return to spawn.

High water temperatures affect the aquatic environment by limiting the amount of dissolved oxygen in the water. At 32°F water can hold 14.6 milligrams of oxygen per liter at saturation. The saturation level decreases to 7.8 milligrams of oxygen per liter at 80°F (7). The latter concentration of oxygen approaches the minimum value recommended by water quality standards.

Growth of bacteria and parasites which can cause disease and death in fish is accelerated in warm water. Brett (4) reported on the devastation of a run of blue-back salmon (Oncorhynchus nerka) in the Columbia River in 1941. At the time of the run, high temperatures in the river promoted the growth of a myxobacterium, Chrondococcus columnaris, lethal to salmon. The bacteria infected the salmon and almost destroyed the run.

Warm water allows "trash" fish such as dace (Rhinichthys sp.) to become

established. These fish increase competition for the available food for the sport and commercial fish. These warm-water fish are better adapted for this competition, causing the cold-water fish to decline in numbers. On a warm trout stream in Michigan, trout made up 14.3 to 19.7% of the total population. At the same time on a nearby cold-water stream, trout comprised 93.8 to 98.7% of the population and accounted for over 99% of the total weight (33).

The growth of algae is stimulated by warm water. The algae produce an undesirable taste, odor, and color in the water, making it less agreeable for human consumption. Also, algae lower the dissolved oxygen content of the water through respiration at night and by increasing the biochemical oxygen demand upon decomposition after death (33).

Cold, clear streams are a great asset to the Northwest. Not only are they an inexpensive source of high-quality drinking water, but they are also a source of income for the region from the fishing and recreation industries. Activities which raise the water temperature in these streams lower the quality of their water and lower their value for several uses.

Stream Temperature and Logging

The adverse effects of logging operations on stream temperatures have been known for a long time. Several intensive studies of this relationship have been conducted. Reports from these studies have indicated that the water temperature can be expected to increase 6° to 28°F if the streams are completely exposed to the sun after logging (7, 8, 14, 22, 31, 34). Changes of these magnitudes can have significant effects upon the aquatic ecosystem.

Although the general impact of logging on stream temperatures was known, the physical processes which caused this impact were not well understood. It was recognized that the source of the heat was solar radiation. However, it was not known how the radiation acted to increase the water temperature. Eschner and Larmoyeux (14) attempted to describe this processes. They

attributed the rise in stream temperature after logging to the entry of warm runoff water into the stream rather than to direct insolation of the stream surface. They theorized that increased soil temperatures after logging produced high ground-water temperatures. This hypothesis must be rejected. The subsurface soil does not become hot enough to have an appreciable effect on the ground-water temperature. Even if the ground-water were heated sufficiently, there is not a large enough volume of runoff in the summer in the Northwest to produce the temperature changes observed within the clear-cuttings.

Energy budgets for exposed and protected streams illustrated why streams increased in temperature after clear-cut logging. The net radiation on exposed streams is up to five times as great as that on protected streams and is responsible for the rise in temperature (5). It can be concluded from this research that temperature problems on small streams can be prevented by maintaining a forest canopy above streams to intercept this radiation.

Water quality standards for small streams created the need for a model that would allow foresters to predict the magnitude of the change in temperature following exposure. A temperature prediction model was developed by Brown (5) using energy budget techniques to assess the heat absorbed by the exposed stream. The model can be written as:

$$\Delta T = \frac{A(H_1)}{D} (C) \qquad (1)$$

where: ΔT = the predicted temperature change in °F.

A = the surface area of the section of the stream exposed by clear-cutting in $ft.^2$.

H_1 = the net radiation absorbed by the stream in $BTU/ft.^2$-min.

D = the stream discharge in cubic feet per second.

C = 0.000267. This constant converts the discharge measurement to pounds of water per minute. ΔT is then expressed in BTU/pound of water which is equivalent to °F.

A subsequent publication by Brown (6) included figures for the calculation of H_1 based on net radiation assuming complete exposure of the stream. This eliminated the need for expensive equipment necessary for the measurement of solar radiation.

The water temperature in any stream is important for the influence it might have on larger streams to which it is tributary. This influence can be calculated with an equation described by Brown (6). This can be written as:

$$\text{Adjusted Temperature} = \frac{D_t(T_t) + D_m(T_m)}{D_t + D_m} \qquad (2)$$

where: D_t and D_m = the discharge of the tributary and main streams respectively in cubic feet per second.

T_t and T_m = the temperature of the tributary and main streams respectively in °F.

The effect of a proposed clear-cutting on the temperature of a tributary system can be predicted with equation 1. The predicted temperature can be used in equation 2 to determine the effect of the proposed clear-cutting on the temperature of the main stream. This approach was used in a U. S. Forest Service study to determine the effects of logging along the tributaries of Steamboat Creek (9).

Methods to calculate the effect of logging on the water temperature of a stream and of the stream system are available. Knowledge of how to prevent these changes is also available. This study was conducted to provide a method for designing minimum sized buffer strips for adequate stream temperature control.

Canopy Density

Buffer strips protect streams from temperature changes by intercepting the incoming solar radiation. The more radiation the canopy is able to intercept, the more shade it can provide for the stream and the better able

it is to control the stream temperature.

Not all of the buffer strip canopy provides shade for the stream. Only that portion of the canopy in the path of the solar radiation shades the stream. Therefore, when measuring the canopy density, it is necessary to measure only this portion of the canopy.

Several types of instruments were considered for this measurement. The first was the "moosehorn" (2, 17, 26). This instrument is a hand-held device designed to provide an estimate of vertical canopy density. The instrument is not satisfactory for measuring angular canopy density since it has no means of angle determination nor any way to hold it steady during measurement. The design of this instrument also makes it impractical for use in buffer strips composed of low growing or bushy vegetation such as salmonberry.

The second instrument considered was the hemispherical densiometer. Two types of densiometers are available; one consists of a curved mirror (21) and the other of a camera fitted with a "fisheye" lens (10, 12). Both are designed to provide estimates of total canopy density. The problem with densiometers is that they cover too much of the canopy; it is too difficult to pick out that portion of the canopy which provides shade to the stream during the critical part of the day. In addition, using the camera proved to be too time consuming. Its use would necessitate two trips to the site instead of one; one trip to take the pictures and a second to set the boundaries for the buffer strip.

The third type of instrument considered was the photoelectric meter (25). The photoelectric meter is designed to measure light intensity. While this would give an indication of the amount of shade the buffer strip was providing, it would not yield any readings helpful in determining the boundaries of the buffer strip.

Because none of the instruments described above were acceptable for

use in this study a new instrument was designed. This is the angular canopy densiometer described in the following section.

SECTION V

STUDY AREAS AND METHODOLOGY

DATA COLLECTION

Description of Study Sites

Study sites were located on nine small streams in Oregon. Three sites, Little Rock, Reynolds, and Francis Creeks, are in the Umpqua National Forest in the southern Cascade Mountains. Five others, Deer, Lake, Grant, Griffith, and Savage Creeks, are in the Siuslaw National Forest in the Coast Range. The remaining stream, Needle Branch, is on land owned by the Georgia Pacific Corporation in the Coast Range.

The streams all flow through or adjacent to clear-cuttings. All have a buffer strip of vegetation which isolates them from the clear-cuttings. All are valuable for fish production and have a potentially large temperature problem.

The main difference between the streams in the Cascades and those in the Coast Range is the amount of vegetation growing around them; the Cascade streams are less densely vegetated. Species common to both areas are: Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco), western hemlock (Tsuga heterophylla [Raf.] Sarg.), western redcedar (Thuja plicata Donn), red alder (Alnus rubra Bong.), bigleaf maple (Acer macrophyllum Pursh), and vine maple (Acer circinatum Pursh). The Coast Range streams are also bordered by salmonberry (Rubus spectabilis Pursh), and Northwest nettle (Urtica gracilis Ait.).

The shade for all of the streams, except for Savage Creek, is provided by the buffer strips; there is no topographic shading. Savage Creek receives its shade from the uncut side of the stream. For this reason, Savage Creek was not included in the analysis.

Four of the streams were divided into two stretches because of

inconsistencies in either the buffer strip or the stream itself. Reynolds Creek was divided at the junction of two distinct types of buffer strips. The strip on the upper stretch was composed almost entirely of scattered clumps of alder. The other contained Douglas-fir, western hemlock, and western redcedar in a continuous strip.

Deer Creek was divided on the basis of both strip and stream characteristics. The upper stretch flows through a broad, flat meadow and is buffered by alder. The lower stretch flows through a steep, V-shaped trough. The principal species in the lower buffer strip is Douglas-fir.

The two stretches of Grant Creek are separated by a large beaver pond. It was not possible to trace the path of the water across the pond. This prevented calculation of the surface area for one long stretch for use in equation 1. Therefore, only stretches above and below the pond were used in the study.

Needle Branch was divided into two 1000-foot sections. This was done in an attempt to obtain an accurate predicted temperature change with equation 1. Examination of the data later revealed a significant inflow of ground-water into the lower stretch. This inflow altered the actual temperature change across the section and had an adverse effect on the analysis of the data.

A more complete description of the study sites is contained in the appendix.

Study Methods

The study methods and instruments were chosen on the basis of availability to the forester. Every instrument is either easily found or constructed; all charts and tables are readily available in published form.

Discharge

Discharge measurements, in cubic feet per second, are necessary to obtain temperature predictions using equation 1. Discharge is a measurement of the volume of water affected by the net energy flux.

Three methods were used to obtain discharge of the streams. On Needle Branch and Deer Creek broad-crested, V-notched weirs maintained by the U. S. Geological Survey were used. Stage and corresponding discharge readings were obtained in the gage house. In both cases, the readings were assumed to be accurate. The influence of tributary streams and ground-water inflow was neglected. This is not a serious omission since the tributary streams were dry and the ground-water inflow was minimal. The low discharge on Needle Branch enabled the ground-water to have a significant effect on the temperature of the stream, but its effect on the discharge was not measurable.

Discharges of the remaining streams, with the exception of Francis Creek, were measured with a Gurley #625 pygmy current meter. Suitable sites were chosen so that an adequate number of velocity readings could be taken across the stream and so that no water could pass the meter unmeasured.

Francis Creek posed a special problem for the measurement of discharge. It was too small to allow the use of the current meter and there was no weir on the stream. Discharge was obtained by measuring the time it took the water, as it exited a culvert, to fill a container of known volume. The measurement was then converted into cubic feet per second.

Travel Time

Travel time is an important component of both the predicted and observed temperature change. Travel time, as used in this study, is the amount of time a parcel of water is exposed to solar radiation. It is used with Figure 2 in Brown (6) to obtain the solar radiation absorbed by the stream. This

is the value H_1 used in equation 1 to predict temperature change.

Travel time was measured by using DuPont Rhodamine B dye. This dye was mixed with acetic acid to a specific gravity of 1.05. The dye was introduced into the stream as it entered the clear-cutting and its movement through the study reach was timed.

Francis Creek again presented a problem. The stream flowed underground in several places in the lower stretch and the dye was filtered out. The travel time of this stretch was calculated as a proportion of that of the upper stretch.

Water Temperature

The actual change in stream temperature as it flowed through the clear-cutting was measured for comparison to the predicted temperature change and for use in later analyses. The water temperature at the top of the reach was used for the equilibrium temperature prediction, as discussed in a later section of this report.

Two methods were used for temperature measurement. Continuous measurements were made using Partlow model TR-112KL thermographs. The sensor for these instruments is a mercury-filled bulb. This bulb is connected to a movable arm by a mercury-filled capillary. A pen attached to the arm records the temperature on a chart connected to a clock. The chart is graduated in 1°F increments, allowing for interpolations to the nearest half-degree. The temperature change observed in a clear-cutting was calculated as the difference between the temperatures recorded on the thermographs at the top of the reach and at the bottom of the reach based on the travel time between them.

The second method made use of a hand-held thermometer which also allowed for interpolation to the nearest half-degree Fahrenheit. Readings were taken at the points where the stream entered and exited the clear-cutting

according to the travel time across the logged unit.

Surface Area

Surface area, as used here, is the amount of the stream exposed to the incoming solar radiation and is the value A used in equation 1. Surface area is the product of the length of the study stretch and the average width of the stretch. Measurements of stream width were taken every 15 feet in order to account for variation encountered in the study streams.

Other temperature studies now in progress have indicated that only the flowing portion of the pools should be included in the estimation of surface area. This portion of a pool was obtained by measuring the path of dye as it moved through the pool.

Net Heat

No instrumentation was used to obtain these data. Net heat was obtained from charts and tables. The heat absorbed by the stream was obtained from Brown (6) using maximum solar angles from List (23) and travel times measured for each study stretch.

Buffer Strip Volume

Timber volume estimates on Reynolds and Lake Creeks were made from diameter and height data taken with a diameter tape and an Abney level. The data were converted into commercial timber volume with the aid of tables found in Forbes (16).

The volume for the remaining strips were supplied through the courtesy of the U. S. Forest Service and the Bureau of Land Management.

Angular Canopy Density

The concept of angular canopy density, ACD, was conceived as a method of

measuring that portion of the buffer strip canopy that actually shades the stream. It is a measure of the percent of the sky between the stream and the sun covered by the canopy at solar noon.

Since none of the instruments described in the literature were satisfactory for the type of measurement required, a new instrument, the angular canopy densiometer, was designed (Figure 1). This instrument consists of a one-foot square plane mirror marked with a three inch grid. The unique feature of the instrument is that it can be tilted so that the observer, looking down vertically on the mirror, will see the canopy along a predetermined angle. The mirror is canted to an angle equal to the complement of the maximum angle of the sun for the period when the temperature problem is greatest. The density provided by the instrument is a measure of the shading ability of the buffer strip. In addition, the forester can see which trees are providing the shade for the stream and make provisions for leaving only these trees or shrubs in the buffer strip.

The angular canopy densiometer was placed in the stream channel at 100-foot intervals. It was pointed south, leveled, and tilted to the proper angle. The ACD was determined by counting the number of squares and fractions of squares covered by the canopy. This was converted into percent. The type of vegetation providing the shade was also recorded for future reference.

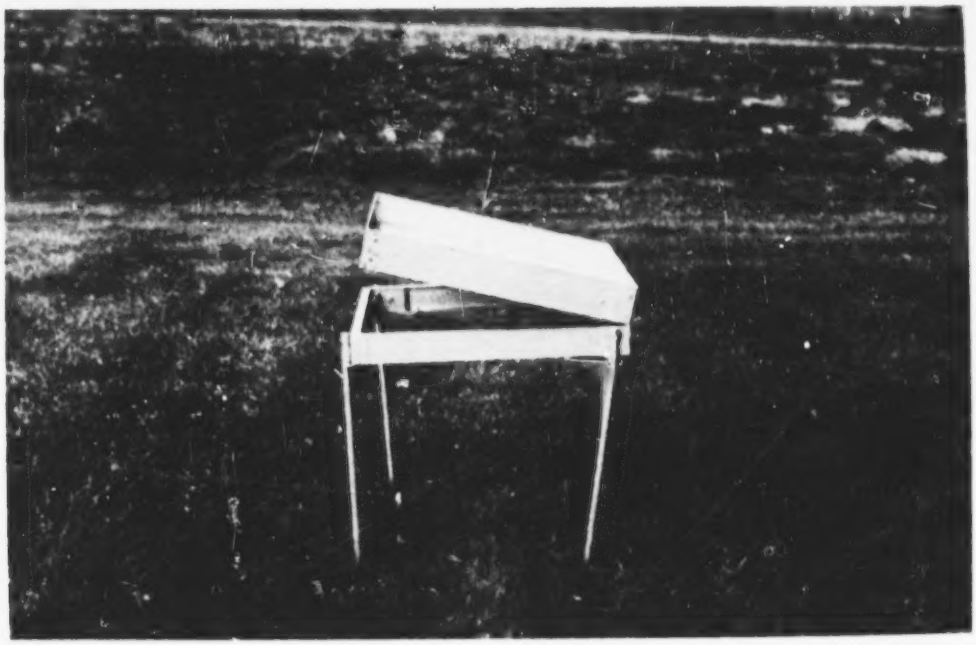

Figure 1. The angular canopy densiometer.

SECTION VI
ANALYSIS OF DATA

A method for evaluating the effectiveness of the buffer strip was considered first in the analysis of data. Several attempts were made to describe the effectiveness of the buffer strip. Most of these were unsuccessful.

Stream temperature alone could not be used because of the effects of clear-cuttings upstream from the study sites. On several streams, these clear-cuttings raised the stream temperatures above acceptable levels before they reached the study areas.

The difference between the observed temperature change and that predicted by assuming complete exposure also proved to be of little value. It is not possible to determine from the difference alone whether a particular buffer strip is effective or not in controlling the water temperature. For instance, a 3°F difference has little meaning unless it is referenced to some specific temperature change. It could be the difference between an observed temperature change of 1°F and a predicted temperature change of 4°F as well as the difference between an observed change of 11°F and a predicted change of 14°F. The two situations are obviously different, but they would appear to be the same with regression analysis.

The same problems occur when buffer strip efficiency is used. The efficiency is calculated as follows:

$$E_f = \frac{T_p - T_A}{T_p} \times 100\% \qquad (3)$$

where: E_f = the buffer strip efficiency in percent.
T_p = the predicted temperature change in °F.
T_A = the observed temperature change in °F.

The efficiency has little significance unless it is referenced to the stream temperature. Regression analysis cannot distinguish between two 50%

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efficiencies even though one may occur when the predicted change is 2°F and the observed change is 1°F and the other when the predicted change is 20°F and the observed change is 10°F. As in the example above, the two are clearly different conditions physically, but not statistically.

Both the difference between the observed and predicted temperature changes and the buffer strip efficiency could be used if all of the streams were equal in size. Then the predicted temperature change would be approximately equal for all streams. The differences in the observed temperature changes along the streams would then be the result of buffer strip differences.

Attempts to equate the streams or standardize according to size met with little success. Length, width, and discharge of each stream would have to be standardized to some common unit. This would require the development of a complicated set of constants which would create an artificial system not well adapted for use by field personnel. This was not done for this reason and because the constants developed would apply only to this set of streams.

The factor decided upon as a measure of buffer strip effectiveness was the amount of incoming radiation which the buffer strip prevents the stream from absorbing. This factor was calculated in two ways. One was to use a rearrangement of equation 1 so that:

$$\Delta H = \frac{(T_P - T_A)D}{AC} \qquad (4)$$

where: ΔH = the heat blocked by the buffer strip in BTU/ft.^{2}-min.

Inadequacies in equation 1 prevented the use of equation 4 for all of the streams in the study. For extremely small streams, such as Francis Creek, equation 1 yields unreasonably high values. Predicted temperature changes ranging from 33° to 626°F were calculated for these streams. These same limitations caused equation 4 to yield extremely low values for ΔH.

It was necessary to find a method for calculating ΔH which was independent

of stream discharge. The method chosen used the equilibrium stream temperature calculated from equations developed by Brady, Graves, and Geyer (3) for predicting equilibrium temperatures in cooling ponds for thermal power plants. The equations are:

$$T = \frac{T_s + T_d}{2} \tag{5}$$

$$B = 0.255 - 0.0085T + 0.000204\ T^2 \tag{6}$$

$$f(U) = 70 + 0.7\ U^2 \tag{7}$$

$$K = 15.7 + (B + 0.26)\ f(U) \tag{8}$$

$$E_t = T_d + \frac{H_s}{K} \tag{9}$$

where: T = the average between the surface temperature at the beginning of the reach, T_s, and the dewpoint temperature, T_d, in °F.

B = the slope of the saturated vapor pressure curve between T_s and T_d in mm Hg/°F.

U = the wind speed in mi./hr.

$f(U)$ = the evaporative wind speed function in BTU/ft.^{2}-day-mmHg.

H_s = the gross solar radiation in BTU/ft.^{2}-day.

K = the heat exchange coefficient in BTU/ft.^{2}-day-°F.

E_t = the equilibrium temperature in °F.

Since the time period for calculation was considerably less than a day, the gross solar radiation, H_s, was adjusted so that it was in terms of BTU/ft.^{2} during the period of time required for the stream to flow through the clearcut. Calculations using this method are in the appendix.

The equilibrium temperature obtained above was then used to obtain the heat blocked by the buffer strip. The heat blocked by the buffer strip can be computed as a percentage of the heat received. This percentage is the difference between the expected and observed temperature change

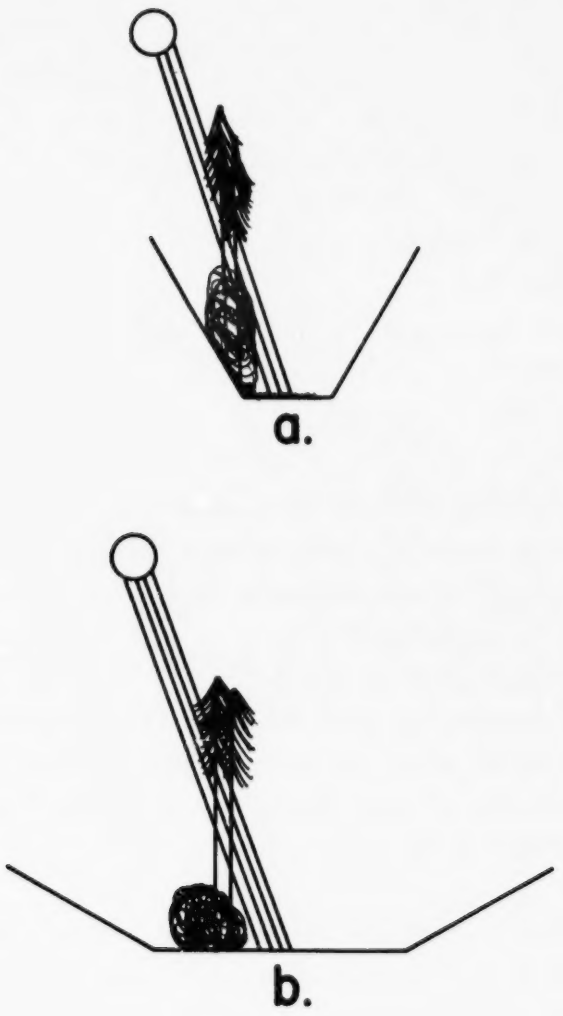

Figure 2. A cross sectional view of the channel shapes of the streams in the study: a. V-shaped channel; b. broad, flat channel.

divided by the expected change. The equation can be written as:

$$\Delta H = \frac{[(E_t - T_s) - T_A]\ [H_1]}{E_t - T_s} \qquad (10)$$

where the quantity $E_t - T_s$ represents the hypothetical or expected temperature change based on the concept of equilibrium temperature.

There are two physiographic problems associated with estimating ΔH. One is the result of ground-water inflow into the stream. The cool ground-water reduces the actual temperature change across the study stretch, giving too large an estimate of the effectiveness of the buffer strip. This is a problem with the lower reaches of Needle Branch and Francis Creek. For this reason, these two study reaches were not used in any of the regression analyses performed in the study.

The second problem stems from the shape of the terrain surrounding the stream. The streams in this study flow through two types of terrain. Most flow through V-shaped troughs. This channel shape makes the forest canopy very effective by aligning more of the canopy in the path of the incoming solar radiation (Figure 2a).

Two study reaches, Little Rock Creek and the upper stretch of Deer Creek, flow through broad, flat areas. This land form often limits the effectiveness of the buffer strip. The canopies in the buffer strips of Little Rock Creek and upper Deer Creek are two-layered. The gap between the layers often permits radiation to strike the stream surface directly (Figure 2b). Also, there is often more of the sky visible directly above the stream in the flat channel, providing a larger source of diffuse radiation. These two factors combine to increase the net radiation available at the stream surface, causing an increase in the temperature change across the study reach. This results in a lower calculated value for ΔH on Little Rock and upper Deer Creeks than on the other streams. These two streams appear to be samples from a different population of conditions. However, the two streams do not provide a large enough sample

to test this hypothesis. All of the figures showing the data have curves calculated without these two streams. The two streams appear on the figures, however, to illustrate these anomalies.

The heat blocked by the buffer strip was compared to the measured buffer strip characteristics. The methods of comparison were both linear and non-linear regression analyses. The analyses were not intended to develop predictive equations. Rather, they were designed to show which of the buffer strip characteristics had the greatest effect on ΔH. There are non-linear, hypothetical models presented along with the actual data. These hypothetical models are based upon ideas developed during the course of this study.

SECTION VII
RESULTS

The influence of buffer strips on temperature control was determined by comparing the heat flow blocked by the strip to the volume of commercial timber within the strip, average strip width, and angular canopy density. The results are presented in three sections, one for each of the buffer strip characteristics studied.

Buffer Strip Volume

One would expect almost no relationship between the volume of the commercial timber in the buffer strip and the ability of the strip to control the temperature of small streams. Dense vegetation with no commercial volume, such as alder or salmonberry thickets, can shade some streams as well or better than a strip which has a large commercial volume. Volume therefore provides no assurance of an effective buffer strip.

This expected lack of relationship can be shown by a hypothetical plotting of ΔH against buffer strip volume (Figure 3). Line A represents some maximum amount of heat the buffer strip can prevent the stream from absorbing. This is the maximum value determined by subtracting the maximum value for net radiation under a closed canopy over a stream from the maximum net radiation above a fully exposed stream. Line A is horizontal since a dense strip with no commercial volume may provide the maximum protection by completely shading the stream. In contrast to this possibility are buffer strips with several thousand board-feet of timber which offer no protection. In these strips, the trees may be too widely spaced to provide an adequate amount of shade or they may be ineffective because of the aspect of the stream or because of their location with respect to the stream. The latter condition is the reason why the buffer strip on Savage Creek is ineffective, even though it contains almost 200,000 board-feet of timber. It is on the east side of the stream. There is, however, some volume at which a buffer strip has a positive effect on the

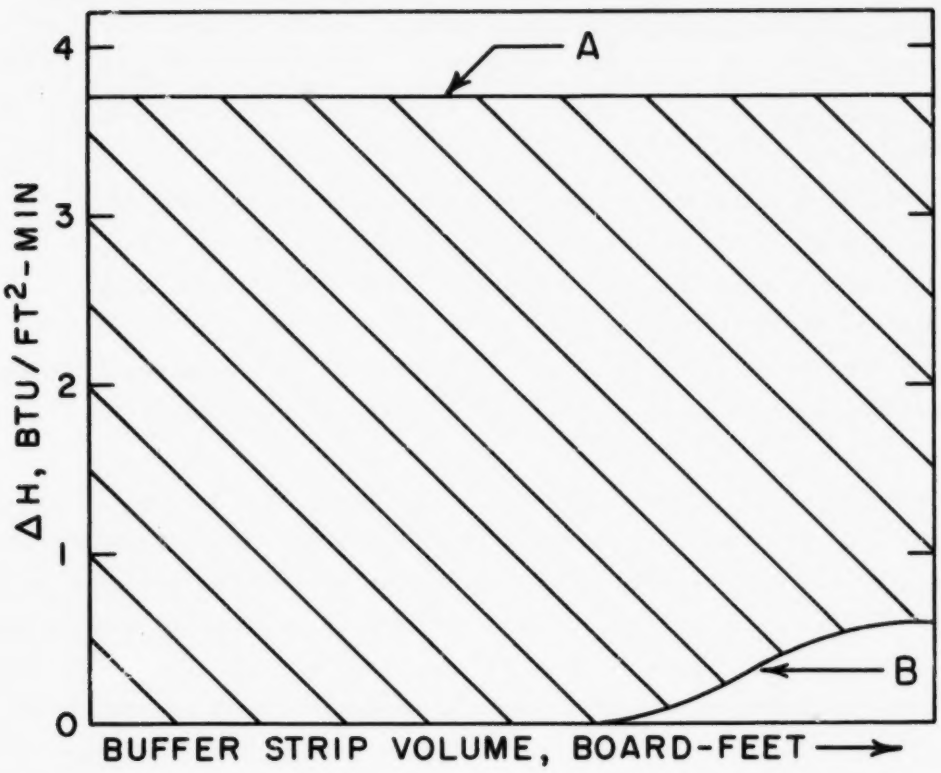

Figure 3. The hypothetical relationship between buffer strip volume and $\triangle$ H.

Table 1. A comparison of the commercial volume of the buffer strips in conifers and the percent of shade contributed by the conifers.

Stream	Commercial volume in conifers[a] (Bd.-Ft.)	Shade contributed by conifers (%)
Little Rock	75.000	87.5
Lower Reynolds	25,118	33.0
Upper Francis	187,885	79.2
Lower Francis	55,145	83.3
Lower Deer	138,830	25.0
Upper Grant	36,073	10.0
Lower Grant	36,073	10.0
Griffith	411,625	74.2
Savage	194,980	0.0

[a]The other buffer strips were composed entirely of hardwood and brushy species of vegetation.

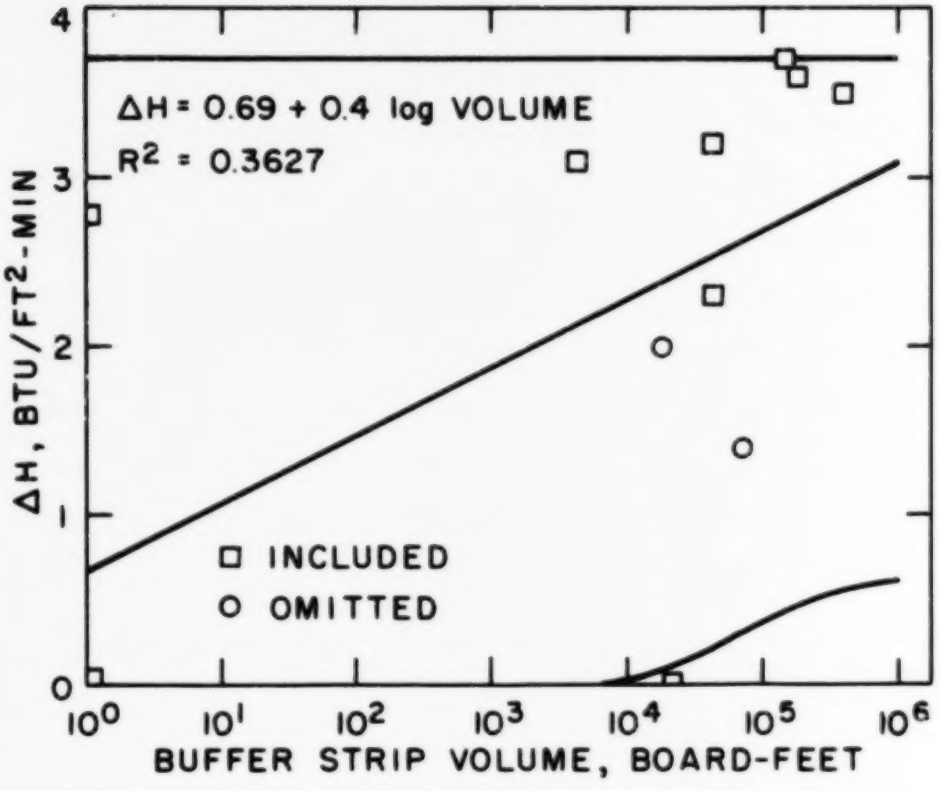

Figure 4. The observed relationship between buffer strip volume and Δ H.

water temperature, assuming that the strip is positioned to shade the stream. At this point, the trees in the strip are close enough together to prevent further increases in the water temperature. This situation is represented by line B.

A listing of the streams which have buffer strips containing some commercial volume in conifers and the percent of shade provided by these conifers is presented in Table 1. Buffer strips composed exclusively of hardwoods are not considered in this study because of the low value of Northwest hardwoods. It can be seen from this table that the shading provided by the commercially valuable trees in the strip varies widely.

The relationship between ΔH and volume found in this study is presented in Figure 4. Superimposed is the hypothetical relationship described in Figure 3. A linear regression analysis of the data is shown in the figure. The R^2 value, 0.3627, is very low indicating poor relationship between the two terms. The strip on the lower stretch of Reynolds Creek illustrates a point made earlier. It has a volume of 25,118 board-feet, yet it provides no protection for the stream. This is because the buffer strip is not uniform. There is almost no protection for the stream for the initial 200 feet of the stretch. Most of the shade is provided by the next 200 feet with the remaining 190 feet being open to the sun again. The shaded portion of the stream is not large enough to prevent the stream temperature from rising the predicted number of degrees.

Buffer Strip Width

Width is the most commonly used term in the design of buffer strips. Guidelines for the management of watersheds frequently specify widths for buffer strips along streams. While these guidelines recognize the need for buffers, they do not recognize the reason buffer strips control temperature. Strip width alone has very little to do with the ability of the vegetation in the strip to shade the stream. Strip width is related to the effectiveness of buffer strips through a complex inter-

relationship of canopy density, canopy height, stream width, and stream discharge.

On very small streams such as those included in this study, the relationship between ΔH and strip width can be viewed as asympototic in nature. The quickness with which the relationship approaches some asymptote is a function of the type of vegetation contained within the strip. Two curves representing a hypothetical relationship between ΔH and strip width for different types of vegetation are shown in Figure 5. Curve A represents very dense, bushy vegetation. These plants do not grow very tall; only those plants adjacent to the stream provide any shade at all. However, their dense foliage is an excellent source of shade. They require only a narrow space along the stream in which to provide the maximum amount of shade. Strips wider than this narrow section should not improve in effectiveness.

Curve B represents a buffer strip composed of trees. Trees have canopies of lower densities than the type of vegetation described above. More space is required to provide an equal amount of protection. This protection cannot be achieved in an equal area because of tree size and spacing. A wider strip is, therefore, required to attain maximum effectiveness when the strip is composed of trees.

The width of the buffer strips on the study streams and the heat blocked by them are presented in Table 2. Only seven streams were used in the statistical analysis of the data. The Reynolds Creek reaches were omitted because of the difficulty in defining strip width. Little Rock Creek and upper Deer Creek were omitted because the shape of the surrounding terrain influenced the heat received at the stream surface. These data are included in Figure 6, however.

Non-linear regression analysis was used to analyze the data. The curve was forced through the origin. The hypothetical maximum, noted in Figure 5, was determined on the basis of a set of conditions not met

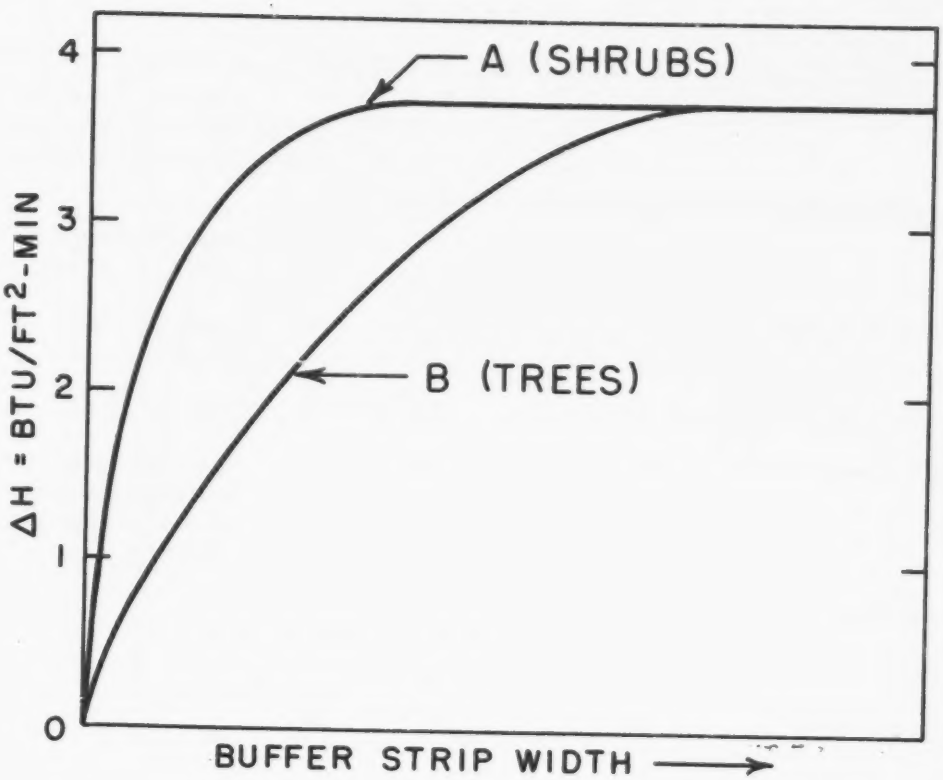

Figure 5. The hypothetical relationship between buffer strip width and △ H.

Table 2. A comparison of buffer strip width with the amount of heat blocked by the strip (ΔH).

Stream[a]	Width (Ft.)	ΔH (BTU/ft.^{2}-min.)	Remarks
Little Rock	47	1.4	omitted from the analysis because of channel shape
Upper Reynolds	10	0.0	omitted from analysis because of strip width
Lower Reynolds	40	0.0	same as upper stretch
Upper Francis	50	3.8	
Upper Deer	100	2.0	omitted from analysis because of the channel shape
Lower Deer	100	3.7	
Lake	30	3.1	
Upper Grant	60	2.3	
Lower Grant	60	3.2	
Griffith	50	3.5	
Upper Needle Branch	8	2.8	

[a]Lower Francis and Lower Needle Branch omitted from the table and analysis because of the inflow of ground-water.

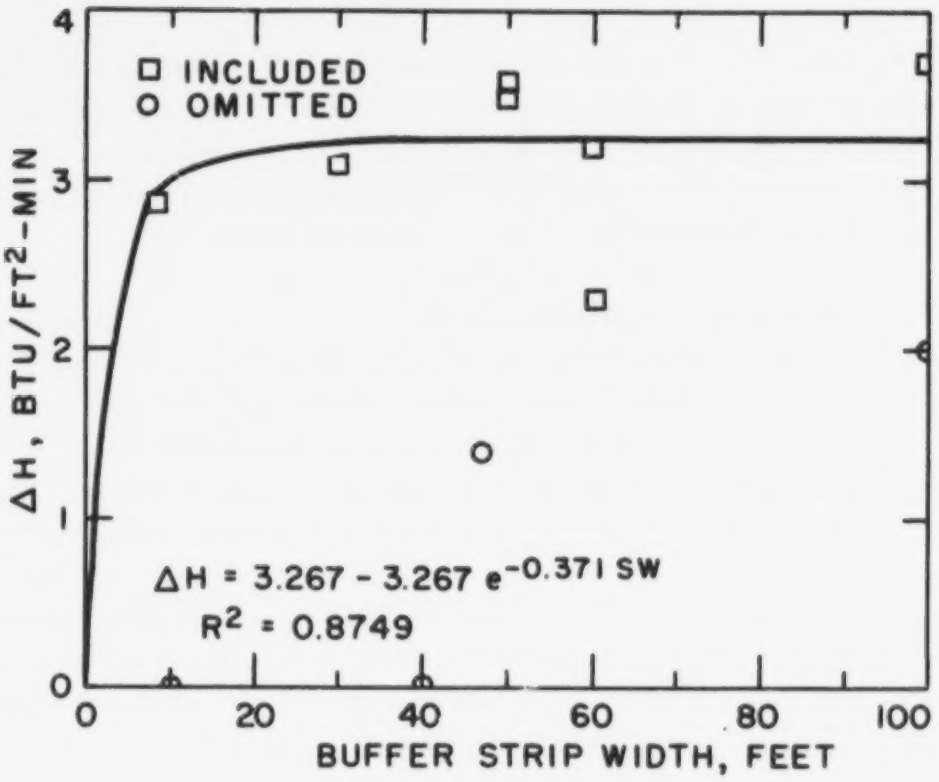

Figure 6. The observed relationship between buffer strip width and Δ H.

on all streams. This is why the curve in Figure 6 is asymptotic at a lower level than hypothesized. However, the curve has a high R^2 value (0.87) indicating that it is a good approximation of the actual process.

Angular Canopy Density

Angular canopy density, ACD, is a measure of the shading ability of the vegetation. By knowing the ACD of the buffer strip, the forester can estimate its effectiveness in controlling water temperature. Design of buffer strips on the basis of ACD assures adequate protection for the stream while allowing for the maximum harvest of timber.

The hypothetical relationship between ΔH and ACD can be considered logistic in nature (Figure 7). Low canopy densities, while reducing the solar radiation incident to the stream in direct proportion to the percent of sky covered, do not provide sufficient shade for the effect to be measurable. Thus, the value for ΔH is zero until some measurement threshold is reached. Above this value, there should be a direct, linear relationship between ΔH and ACD until the canopy approaches full closure. As the canopy density approaches 100 percent, additional increments of density should block less radiation than the previous increment. This is because that at high canopy densities, the possibility for reflection and absorbtion of the incident radiation increases allowing mostly diffuse radiation to reach the stream. The level of this diffuse radiation is controlled by factors other than canopy density. The volume of vegetation in the canopy influences the amount of transmission. Thicker canopies, such as conifers provide, are more efficient radiation traps than thin canopies, such as hardwoods provide, even though the canopy density may be the same. Thus, with greater canopy density, the relationship between ΔH and ACD should approach some asymptote at a level less than complete blockage of incident radiation. Values of ΔH for undisturbed canopies are in the range of 3.0 to 3.6 BTU/ft^{2}min (5, 9). This corresponds with values calculated in this study.

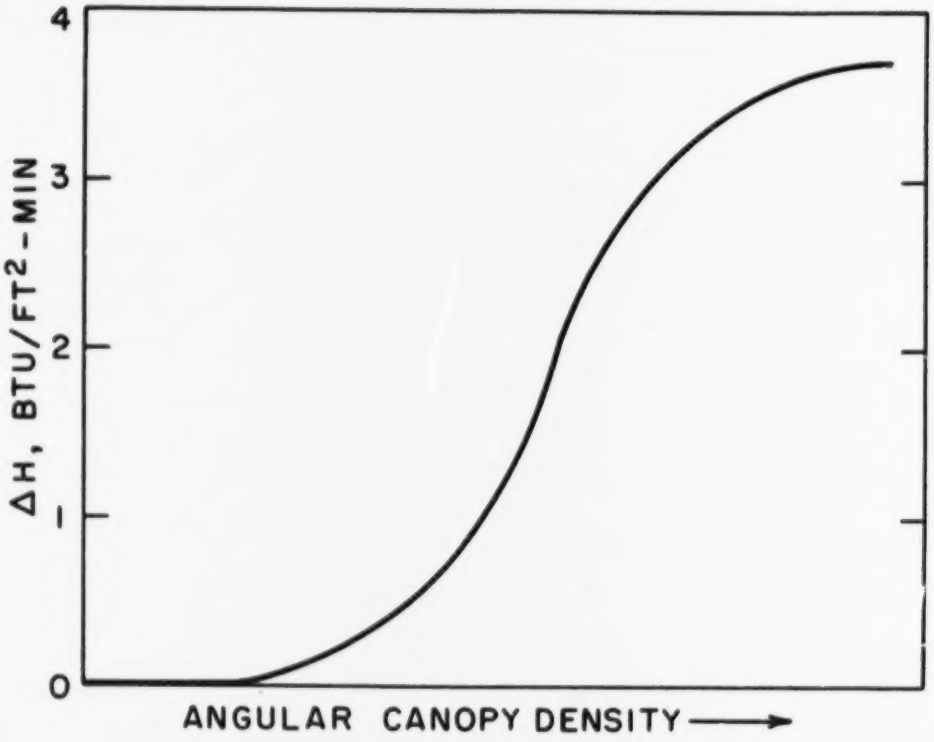

Figure 7. The hypothetical relationship between angular canopy density and ΔH.

Table 3. A comparison of the angular canopy density (ACD) of the buffer strips with the amount of heat blocked by the strips (ΔH).

Stream[a]	ACD (%)	ΔH (BTU/ft.^{2}-min.)	Remarks
Little Rock	73.6	1.4	omitted from analysis because of channel shape
Upper Reynolds	18.3	0.0	
Lower Reynolds	46.9	0.0	
Upper Francis	75.9	3.8	
Upper Deer	80.3	2.0	omitted from analysis because of channel shape
Lower Deer	78.3	3.7	
Lake	77.7	3.1	
Upper Grant	59.1	2.3	
Lower Grant	65.2	3.2	
Griffith	79.1	3.5	
Upper Needle Branch	55.6	2.8	

[a]Lower Francis and Lower Needle Branch omitted from table and analysis because of influence of ground-water on temperature.

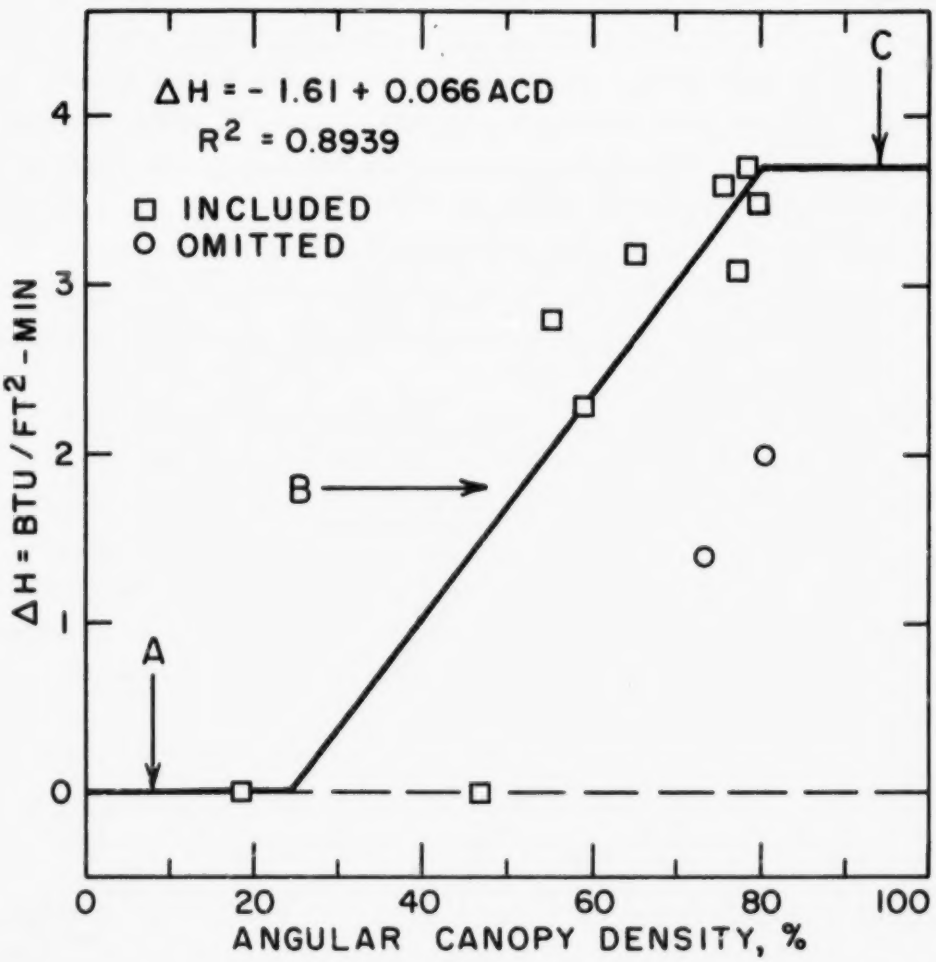

Figure 8. The observed relationship between angular canopy density and ΔH.

The ACD's for the study streams are presented in Table 3. Little Rock and upper Deer Creeks are again omitted from the analysis because of the surrounding terrain. Problems with the computer programs prevented fitting a logistic curve to the data. For this reason, a straight-line approximation to the logistic curve was used (Figure 8). Segment A represents the ACD values below the threshold level, which occurs at about 23% with these data. This point was determined by the linear regression analysis used for segment B. Line segment B is the section of increasing buffer strip effectiveness with increasing ACD. The line fits the data well with an R^2 value of 0.89. Segment C is the area of maximum protection. The maximum was determined from the net radiation over protected and exposed streams as explained earlier. Once the maximum protection has been reached, increases in ACD offer no greater protection.

The lower reach of Reynolds Creek is anomalous to the relation mentioned above. Although the buffer strip completely shades 200 feet of the reach and has an average ACD of 46.9% over the entire reach, it is ineffective in controlling the stream temperature. The observed temperature change (3°F) exceeds that predicted (1.6°F). However, the two changes must be considered similar because of the accuracy of equation 1. The reach was resurveyed in an unsuccessful attempt to explain the anomaly.

SECTION VIII
DISCUSSION

Buffer strips are an effective means of controlling stream temperatures. The predicted maximum and observed maximum temperatures for all study streams are presented in Figure 9. With the exception of Reynolds Creek, all of the observed water temperatures are lower than the predicted temperatures. Nine of the streams have predicted maximum temperatures above 65°F, but only four have observed maximums that high. Three of the four, Little Rock Creek and both reaches of Reynolds Creek, had temperatures above 65°F when they entered the study sections. The upper reach of Needle Branch was the other stretch that exceeded a temperature of 65°F. Its temperature rose only to 67°F. This is a full 12°F below the predicted maximum temperature for this stream. This difference is due primarily to the effect of the buffer strip.

It has been known for a long time that the presence of a well-designed buffer strip will control stream temperatures. What has not been known is which characteristics of buffer strips are important in this control. The data indicate that the commercial timber volume contained in the buffer strip is not an important criterion for temperature control. The effectiveness of the strip is not well related to timber volume.

Strip width beyond some minimum value (about 30 feet in this study) is not an important criterion for stream temperature control. The use of a 100 to 200-foot standard width for all buffer strips will assure adequate protection for most streams. However, this practice usually results in more trees than necessary to provide adequate protection. The width of each buffer strip studied and its canopy density are plotted in Figure 10. These data indicate that for the average buffer strip, the maximum ACD, and hence the maximum shading ability, is reached within a width of 80 feet. Moreover, 90% of that maximum is reached within 55 feet.

The maximum effective width presented here differs from that in Figure 6 for several reasons. The most important of these is that the

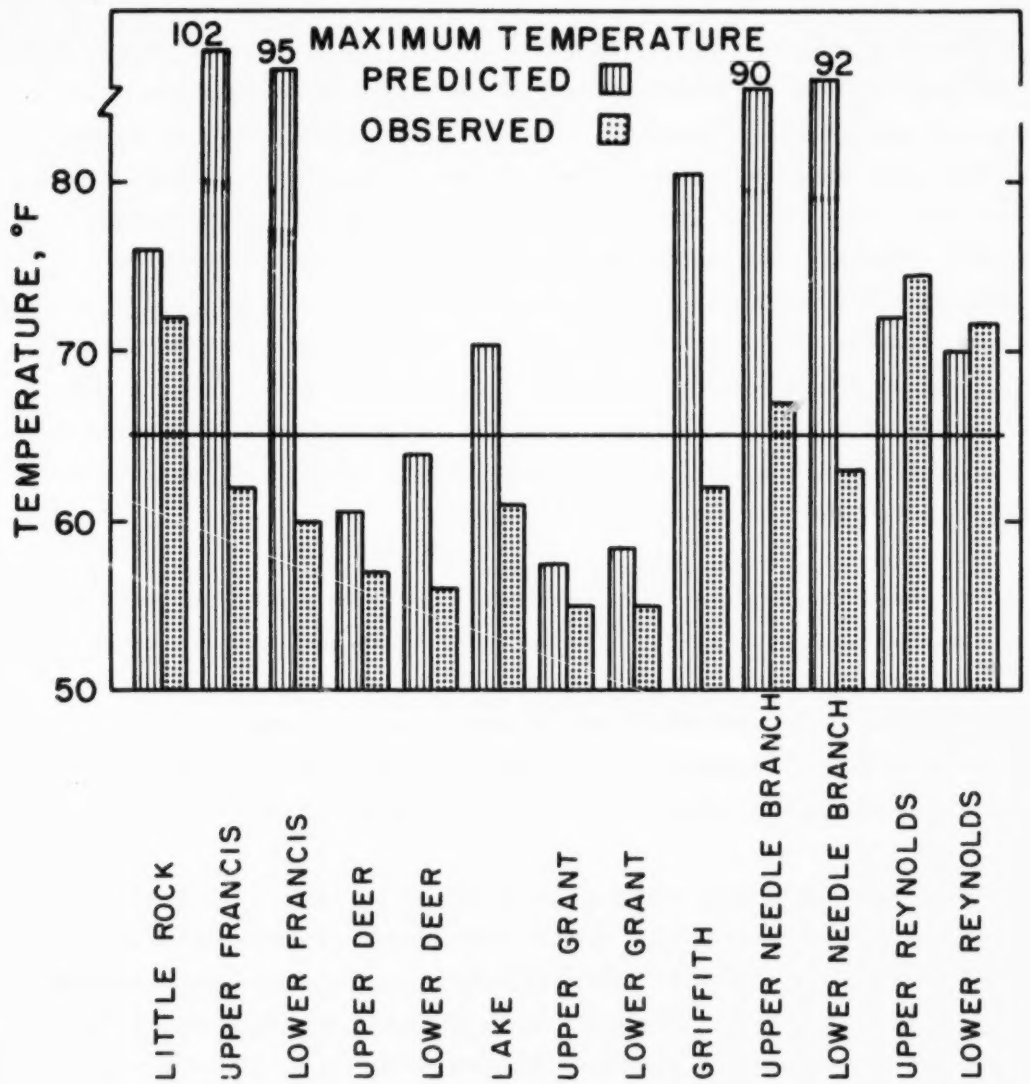

Figure 9. A comparison of the predicted maximum and observed maximum stream temperatures.

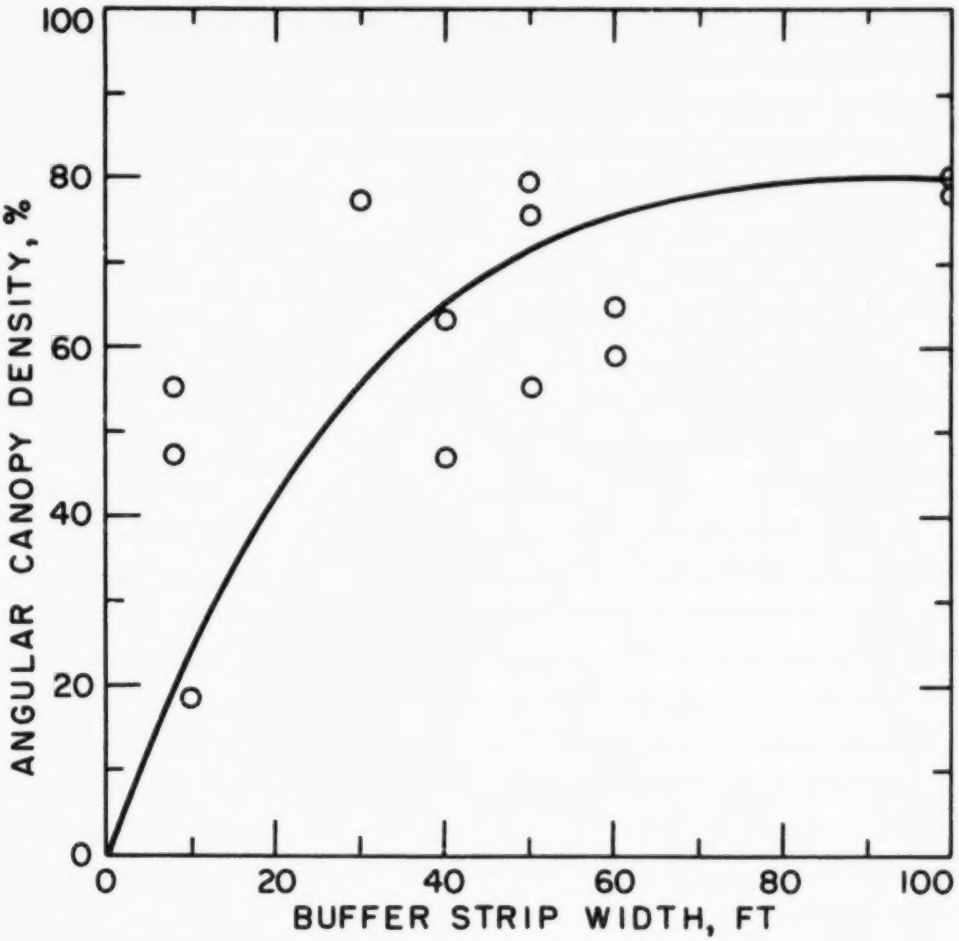

Figure 10. The relationship between buffer strip width and angular canopy density.

relationship described in Figure 6 is based on the interrelationship between buffer strip width and canopy density and height, and stream width and discharge. The relationship in Figure 10 is based only on strip width and angular canopy density. In addition, all of the study streams were included in Figure 10, whereas several were omitted in Figure 6. The large amount of variance exhibited by the buffer strips limited the effectiveness of regression analysis in describing the relationship presented in Figure 10. For this reason, a hand-fitted curve has been used to describe the relation between the two factors.

Angular canopy density is the only buffer strip parameter which is strongly correlated with stream temperature control. It is the only measure the forester can use that will assure him of providing enough shade for the stream without overdesigning the buffer strip. ACD incorporates the variation imposed by different vegetation types and stream configurations. It is for this reason that the design of buffer strips must be done site by site. In this way, vegetation providing the maximum ACD can be preserved in each buffer strip. Design of the strip on this basis allows for a consistent level of protection on each stream. The normal temperature regime of each stream should not change when this method of planning is used because the natural surroundings of the stream which influence its temperature are not changed. This is in line with existing water quality standards. At the minimum, the ACD should be maintained at 80% on all fully covered streams; for streams with pre-logging ACD less than 80%, ACD should not be reduced below the natural condition.

When designing a buffer strip, the forester should be aware of several other factors. He should be cognizant of the aspect of the stream and the placement of the clear-cutting with respect to the stream. Since the sun never shines from the north in this region, there is no need for a buffer strip for temperature control on the north side of the stream.

There is also little need for a buffer strip on the east side of a

stream. Stream temperatures do not peak until afternoon when the sun shines from the southwest. The buffer strip on the east side of the stream would offer no protection. This is the case on Savage Creek.

Streams that flow north-south present a special problem. At solar noon the sun can shine straight up the stream. The only protection for these streams comes from overtopping vegetation on both sides of the stream. Side shading will have no effect until the sun is past its zenith.

Buffer strips should vary with the size of the stream. The forester should take advantage of all of the brushy vegetation available; in many instances such vegetation is sufficient to provide temperature control.

Foresters should design buffer strips with a uniform canopy density. Large gaps, such as those on Reynolds Creek, lower the effectiveness of the strip. The reason for this lack of effectiveness seems to be that even with 100 percent canopy density, isolated patches of trees provide much less than complete blockage of the incident radiation. Transmission through the canopy and reflection from the unforested zones at each end of the isolated strip of trees combine to reduce the heat it blocks. Thus, the heat blocked by a buffer strip that is half completely exposed and half completely shaded should be much less than that blocked by a continuous canopy with 50 percent density.

Buffer strips decline in effectiveness as the streams increase in size (Figure 11). Small streams have the greatest temperature problem. This is because of the inverse relationship between temperature change and discharge (equation 1). Buffer strips are very effective for the control of water temperatures on these small streams. On larger streams, such as Steamboat Creek, buffer strips have little effect on the water temperature (9). One reason for this is the volume of water in the stream. Another reason is that it is physically impossible for the

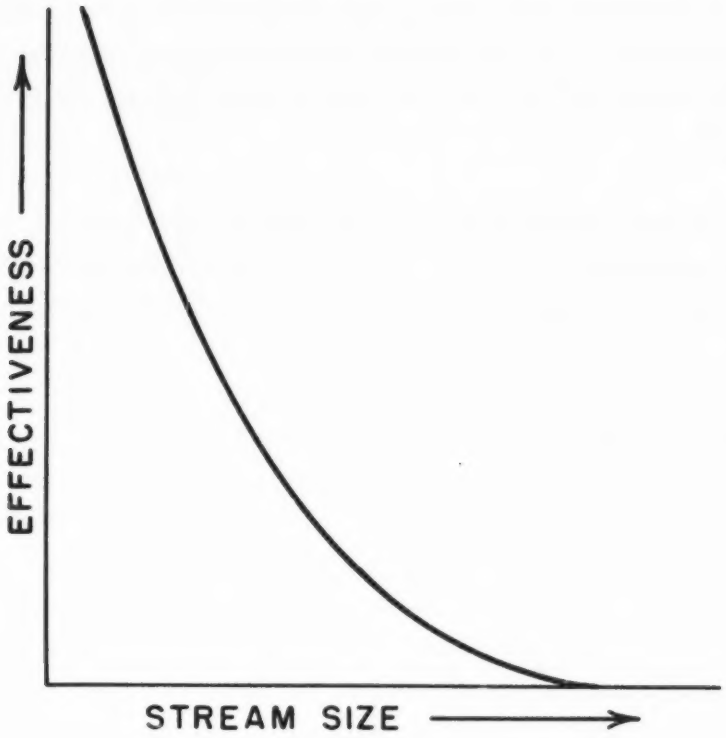

Figure 11. The decline in importance of buffer strips for temperature control with increasing stream size.

vegetation to shade more than a small portion of the stream during the periods of peak radiation density.

For most of the small forest streams adjacent to clear-cuttings, temperature problems can be controlled by buffer strips. This study has presented a method for designing buffer strips to provide the maximum protection to the stream with the minimum amount of timber. This information will help preserve the water quality of a stream while allowing for the optimum utilization of the timber resource.

SECTION IX

ACKNOWLEDGEMENTS

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SECTION X

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SECTION XI

APPENDIX

Table A. A comparison of various measured and calculated parameters for the study streams.

Stream	Predicted temperature change	Observed temperature change	ΔH BTU/ft.^{2}-min.	ACD %	Strip width Ft.	P-A[a] °F	Volume Bd.-Ft.	Observed maximum temperature °F	Predicted maximum temperature °F
Little Rock	10.1	6.0	1.4	73.6	47	4.0	75,000	72	76
Upper Reynolds	4.8	7.5	0.0	18.3	10	2.7	0	74.5	72
Lower Reynolds	1.6	3.0	0.0	46.9	40	1.4	25,118	71.5	70
Upper Francis	41.9[b]	2.0	3.8	75.9	50	39.9	187,885	62	101.9
Lower Francis	35.7[b]	1.0	3.9	55.3	50	34.7	55,145	60	94.7
Upper Deer	7.6	4.0	2.0	80.3	100	3.6	18,745	57	60.5
Lower Deer	9.0	1.0	3.7	78.3	100	7.9	138,830	56	64
Lake	12.5	3.0	3.1	77.7	30	9.5	4,392	61	70.5
Upper Grant	4.4	2.0	2.3	59.1	60	2.4	38,245	55	57.5
Lower Grant	4.3	1.0	3.2	65.2	60	3.3	38,245	55	58.5
Griffith	21.7	3.0	3.5	79.1	50	18.7	413,260	62	80.5
Upper Needle Branch	32	9.0	2.8	55.6	8	23	0	67	90
Lower Needle Branch	32	3.0	2.8	47.6	8	29	0	63	92

[a]The predicted temperature change - the actual temperature change.

[b]Predicted from the equilibrium temperature calculation.

EQUILIBRIUM TEMPERATURE CALCULATION

$$T = \frac{T_s + T_d}{2} \tag{5}$$

$$B = 0.255 - 0.0085\ T + 0.000204\ T^2 \tag{6}$$

$$f(U) = 70 + 0.7\ U^2 \tag{7}$$

$$K = 15.7 + (B + 0.26)\ f(U) \tag{8}$$

$$E = T_d + \frac{H_s}{K} \tag{9}$$

For the upper stretch of Francis Creek:

Travel time = 3 hours

T_{air} = 95°F

RH = 50%

U = 2 mph

T_d = 71°F

T_s = 60°F

H_s = 4.0 BTU/ft.^{2}-min.
= 720 BTU/ft.^{2}-3 hours

$$T = \frac{71 + 60}{2} = 65.5°F$$

$B = 0.255 - 0.0085\ (65.5) + 0.000204\ (65.5^2) = 0.573$ mm Hg/°F

$f(U) = 70 + 0.7\ (2^2) = 9.09$ BTU/ft.^{2}-3 hours-mm Hg.

$K = 15.7 + (0.573 + 0.26)\ (9.09) = 23.27$ BTU/ft.^{2}-3 hours-°F.

$$E = 71 + \frac{720}{23.27} = 101.9°F$$

Predicted temperature change = 101.9 - 60 = 41.9°F.

SITE DESCRIPTIONS

Little Rock Creek

Aspect: east-west flow, buffer strip on south side.

Vegetation: alder, Douglas-fir, western redcedar, bigleaf maple.

Travel Time: 1-1/3 hours.

Discharge: 1.16 CFS.

Stream Width: 8.7 feet.

Stream Length: 1500 feet.

Surface Area: 13050 square feet.

Strip Width: 47 feet.

Strip Volume: 75,000 bd.-ft.

Angular Canopy Density: 73.6%.

Heat Load: 4.2 BTU/ft.^{2}-min.

Predicted Temperature Change: 10.1°F.

Actual Temperature Change: 72° - 66° = 6°F.

ΔH: 1.4 BTU/ft.^{2}-min.

Reynolds Creek, upper stretch

Aspect: northwest-southeast flow, strip on the southwest side.

Vegetation: alder, western hemlock, vine maple. (Primarily regrowth following logging.)

Travel Time: 1 1/4 hours.

Discharge: 2.51 CFS.

Stream Width: 7.3 feet.

Stream Length: 1850 feet.

Surface Area: 13505 square feet.

Strip width: 10 feet.

Strip Volume: 0 bd.-ft.

Angular Canopy Density: 18.3%

Heat Load: 4.2 BTU/ft.^{2}-min.

Predicted Temperature Change: 4.8°F.

Actual Temperature Change: 74.5° - 67° = 7.5°F.

ΔH: 0 BTU/ft.^{2}-min.

Reynolds Creek, lower stretch

Aspect: northwest-southeast flow, strip on the southwest side.

Vegetation: alder, Douglas-fir, western redcedar, western hemlock, vine maple.

Travel Time: 1/2 hour.

Discharge: 2.51 CFS.

Stream Width: 7.7 feet.

Stream Length: 590 feet.

Surface Area: 4543 square feet.

Strip Width: 40 feet.

Strip Volume: 25,118 bd.-ft.

Angular Canopy Density: 46.9%.

Heat Load: 4.2 BTU/ft.^{2}-min.

Predicted Temperature Change: 1.6°F.

Actual Temperature Change: 70° - 67° = 3°F.

ΔH: 0 BTU/ft.^{2}-min.

Lake Creek

Aspect: east-west flow, strip on the south side.

Vegetation: alder, bigleaf maple, salmonberry, Northwest nettle.

Travel Time: 2-1/6 hours.

Discharge: 0.71 CFS.

Stream Width: 4.5 feet.

Stream Length: 1800 feet.

Surface Area: 8100 square feet.

Strip Width: 30 feet.

Strip Volume: 4392 square feet.

Angular Canopy Density: 77.7%.

Heat Load: 4.1 BTU/ft.^{2}-min.

Predicted Temperature Change: 12.5°F.

Actual Temperature Change: 61° - 58° = 3°F.

ΔH: 3.1 BTU/ft.^{2}-min.

Francis Creek, upper stretch

Aspect: east-west flow, buffer strip on the south side.

Vegetation: vine maple, western redcedar, western hemlock, Douglas-fir.

Travel Time: 3 hours.

Discharge: 0.01 CFS.

Stream Width: 1 foot.

Stream Length: 2400 feet.

Surface Area: 2400 square feet.

Strip Width: 50 feet.

Strip Volume: 187,885 bd.-ft.

Angular Canopy Density: 75.9%.

Heat Load: 4.0 BTU/ft.^{2}-min.

Predicted Temperature Change: 41.9°F.

Actual Temperature Change: 62° - 60° = 2°F.

ΔH: 3.8 BTU/ft.^{2}-min.

Francis Creek, lower stretch

Aspect: east-west flow, buffer strip on the south side.

Vegetation: vine maple, western redcedar, western hemlock, Douglas-fir.

Travel Time: 2 hours.

Discharge: 0.01 CFS.

Stream Width: 3.1 feet.

Stream Length: 1700 feet.

Surface Area: 5720 square feet.

Strip Width: 50 feet.

Strip Volume: 55,145 bd.-ft.

Angular Canopy Density: 55.3%.

Heat Load: 4.1 BTU/ft.^{2}-min.

Predicted Temperature Change: 35.7°F.

Actual Temperature Change: 60° - 59° = 1°F.

ΔH: 3.9 BTU/ft.^{2}-min.

Deer Creek, upper stretch

Aspect: north-south flow, buffer strip on the west side.

Vegetation: alder, Douglas-fir, salmonberry.

Travel Time: 2-3/4 hours.

Discharge: 0.74 CFS.

Stream Width: 3.1 feet.

Stream Length: 1650 feet.

Surface Area: 5115 square feet.

Strip Width: 100 feet.

Strip Volume: 18,745 bd.-ft.

Angular Canopy Density: 80.3%.

Heat Load: 4.1 BTU/ft.^{2}-min.

Predicted Temperature Change: 7.6°F.

Actual Temperature Change: 57° - 53° = 4°F.

ΔH: 2.0 BTU/ft.^{2}-min.

Deer Creek, lower stretch

Aspect: north-south flow, buffer strip on the west side.

Vegetation: alder, Douglas-fir, salmonberry.

Travel Time: 1-1/3 hours.

Discharge: 0.74 CFS.

Stream Width: 4.4 feet.

Stream Length: 1350 feet.

Surface Area: 5940 square feet.

Strip Width: 100 feet.

Strip Volume: 138,830 bd.-ft.

Angular Canopy Density: 78.3%.

Heat Load: 4.2 BTU/ft.^{2}-min.

Predicted Temperature Change: 9.0°F.

Actual Temperature Change: 56° - 55° = 1°F.

ΔH: 3.7 BTU/ft.^{2}-min.

Grant Creek, upper stretch

Aspect: north-south flow, buffer strip on the west side.

Vegetation: alder, Douglas-fir, salmonberry.

Travel Time: 5/6 hour.

Discharge: 1.12 CFS.

Stream Width: 4.9 feet.

Stream Length: 900 feet.

Surface Area: 4410 square feet.

Strip Width: 60 feet.

Strip Volume: 38,245 bd.-ft.

Angular Canopy Density: 59.1%.

Heat Load: 4.2 BTU/ft.^{2}-min.

Predicted Temperature Change: 4.4°F.

Actual Temperature Change: 55° - 53° = 2°F.

ΔH: 2.3 BTU/ft.^{2}-min.

Grant Creek, lower stretch

Aspect: north-south flow, buffer strip on the west side.

Vegetation: alder, Douglas-fir, salmonberry.

Travel Time: 2/3 hour.

Discharge: 1.12 CFS.

Stream Width: 4.8 feet.

Stream Length: 900 feet.

Surface Area: 4320 square feet.

Strip Width: 60 feet.

Strip Volume: 38,245 bd.-ft.

Angular Canopy Density: 65.2%.

Heat Load: 4.2 BTU/ft.^{2}-min.

Predicted Temperature Change: 4.3°F.

Actual Temperature Change: 55° - 54° = 1°F.

ΔH: 3.2 BTU/ft.^{2}-min.

Needle Branch, upper stretch

Aspect: north-south flow, buffer strip on west side.

Vegetation: alder (regrowth after logging).

Travel Time: 3 hours.

Discharge: 0.08 CFS.

Stream Width: 2.4 feet.

Stream Length: 1000 feet.

Surface Area: 2400 square feet.

Strip Width: 8 feet.

Strip Volume: 0 bd.-ft.

Angular Canopy Density: 55.6%.

Heat Load: 4.0 BTU/ft.^{2}-min.

Predicted Temperature Change: 32°F.

Actual Temperature Change: 67° - 58° = 9°F.

ΔH: 2.8 BTU/ft.^{2}-min.

Needle Branch, lower stretch

Aspect: north-south flow, buffer strip on west side.

Vegetation: alder (regrowth after logging).

Travel Time: 3 hours.

Discharge: 0.08 CFS.

Stream Width: 2.4 feet.

Stream Length: 1000 feet.

Surface Area: 2400 square feet.

Strip Width: 8 feet.

Strip Volume: 0 bd.-ft.

Angular Canopy Density: 47.6%.

Heat Load: 4.0 BTU/ft.^{2}-min.

Predicted Temperature Change: 32°F.

Actual Temperature Change: 63° - 60° = 3°F.

ΔH: 2.8 BTU/ft.^{2}-min.

Griffith Creek

Aspect: east-west flow, buffer strip on the south side.

Vegetation: alder, Douglas-fir, western hemlock, vine maple, bigleaf maple.

Travel Time: 2-1/3 hours.

Discharge: 1.3 CFS.

Stream Width: 8.6 feet.

Stream Length: 3000 feet.

Surface Area: 25,800 square feet.

Strip Width: 50 feet.

Strip Volume: 413,260 bd.-ft.

Angular Canopy Density: 79.1%.

Heat Load: 4.1 BTU/ft.^{2}-min.

Predicted Temperature Change: 21.7°F.

Actual Temperature Change: 62° - 59° = 3°F.

ΔH: 3.5 BTU/ft.^{2}-min.

Savage Creek

Aspect: north-south flow, buffer strip on the east side.

Vegetation: alder, Douglas-fir, salmonberry.

No other information was taken on Savage Creek because the location of the buffer strip prevented it from having any effect on the temperature of the stream.